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How information and communication technology drives carbon emissions: A sector-level analysis for China

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ABSTRACT

Understanding the carbon implications of information and communication technology (ICT) is critical for tackling climate change challenges in the digital era. This paper develops an embodied carbon analysis framework by integrating input-output approaches to explore the extent to which and how ICT drives carbon emissions at the sector level. With the proposed framework, we not only assess the carbon emissions embodied in various ICT subsectors but also reveal the formation and changing mechanism by identifying their source sectors, transfer paths, and economic drivers. Using China as a case study, we find that ICT sector is far from being environment-friendly while considering its embodied carbon impacts, which are dozens of times greater than the direct impacts. This is because ICT sector can induce significant amounts of emissions through its requirement for carbon-intensive intermediate inputs from non-ICT sectors. The *electricity* sector and basic material sectors (e.g. *chemicals*, *metal*, and *non-metal*) are the most important carbon sources, and are involved in major carbon transfer paths. The fast growth of embodied emissions in ICT sector is driven by the large-scale expansion of final demand for ICT products, although improvements in upstream production efficiency have largely slowed the growth. We suggest that integrated carbon management strategies incorporating mitigation measures for specific sectors, supply chains, and economic drivers are particularly required for addressing ICT-related carbon emission issues.

1. Introduction

Few would dispute that information and communication technology (ICT) has fundamentally transformed economies, societies, and the environment worldwide. There have been successive ICT revolutions over the past few decades, from the invention of transistors and integrated circuits around the 1950s, to the proliferation of radios, TVs, personal computers (PCs), software, and the Internet during the 1970–2000s, and further to the boom of wireless networks, cloud computing, big data, and artificial intelligence today (Berndt and Rappaport, 2001). The emergence and popularization of ICT is commonly deemed societally and economically beneficial, since it creates a wide array of opportunities, cost savings and conveniences such as spawning technological innovation, improving productivity, and facilitating human communication (Melville, 2010; Chun et al., 2015; Olesen and Myers, 2013). In terms of the environment, however, a general consensus has yet to be reached. Some studies argue that ICT can improve the environment through its applications in optimizing production processes and enabling better environment management (Feuerriegel et al., 2016; Røpke, 2012; Cecere et al., 2014). Others express their concerns about the environmental consequences (e.g. electricity consumption, e-waste) caused by the manufacturing, operation, and disposal of ICT devices (Williams, 2011; Fettweis and Zimmermann, 2008; Collard et al., 2005). To seek synergy between large-scale ICT development and environment protection actions in the digital era, scholars, policymakers, and practitioners need a better understanding of how ICT interact with the environment.

There have been a growing number of studies discussing the carbon implications of ICT considering that curbing the growth of carbon emissions to combat against climate change has become global consensus. Scholars have quantitatively assessed the ICT-related carbon impacts from different levels. At the product level, life cycle assessments (LCA) on ICT devices and services such as smartphones, networks, data centers, and cloud servers have revealed that ICT could cause considerable whole-process carbon emissions. Ercan et al. (2016) calculated the global warming potential for a Sony smartphone including accessories to be 57 kg CO_2 equivalent for an operating time of 3 years. Emmenegger et al. (2006) analyzed the carbon footprint of mobile communication systems in Switzerland based on LCA method, suggesting that about 25 kg CO_2 were emitted while transferring 1 Gbit information from mobile to mobile network and 20 kg CO_2 from mobile to fixed network.

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Honee et al. (2012) assessed the carbon footprint of data centers through an LCA case study of the Swedish insurance administration, showing that more than half of the carbon footprint is relative to the PC equipment fleet. Thakur and Chaurasia (2016) proposed a suite of metrices for measuring CO_2 emission in cloud computing, finding that the data center and cloud servers are the prime source of carbon footprint. A most recent review on the LCA-based approaches to assess the environmental effects of ICT application can be found in Pohl et al. (2019). These studies have set up a common standard for process-based LCA of carbon emissions generated by ICT products, but they still lack comparability in results owing to the high uncertainties and variabilities in defining system boundary, collecting data, and setting parameters (Weber et al., 2010).

At the national level, recent econometric studies have found that the overall contributions of ICT development to carbon emissions varied significantly across regions and sectors. Moyer and Hughes (2012) explored the dynamic effects of ICT on economic and energy systems, and resultant carbon emissions, concluding that ICT could have a limited downward impact on carbon emissions. Higón et al. (2017) argued there was an inverted U-shaped relationship between ICT and CO_2 emissions, suggesting that developing countries had higher turning points of ICT development level than developed countries. Asongu et al. (2017, 2018) examined how increasing ICT (i.e. internet and mobile phones) penetration in sub-Saharan Africa could decrease CO_2 emissions, and computed the required minimum ICT levels at which the net emission effects could be negative. Shabani and Shahnazi (2019) investigated the relationship between energy consumption, gross domestic product, CO_2 emissions, and ICT in Iranian economic sectors, suggesting the positive effect of ICT on CO_2 emissions in the industrial sector, and the negative effect in the transportation and services sectors. While these studies succeeded in estimating the overall effects of ICT development on carbon emissions, they failed to unveil the mechanisms that underlie the dynamic effects. Moreover, treating ICT as a homogeneous whole would make it hard to distinguish the roles played by different ICT branches, or disentangle the intertwined relationships between ICT and other sectors.

At the sector level, there is a relative dearth of studies concerning the carbon emissions of ICT since ICT sector is so inconspicuous while looking at its direct emissions. For instance, the CO_2 emissions of China's ICT sector in 2012 were around 7 million tonnes (Mt), accounting for less than 0.1% of the total emissions (Pan et al., 2017). This gives us a perception that ICT sector is environment-friendly, thus it is not necessary to investigate its emissions. However, some scholars have found that the carbon footprint of ICT sector could be considerable. GeSI (2015) roughly predicted the carbon footprint of ICT sector would reach 1.25 Gigatons (Gt) of CO_2 in 2030, accounting for 1.97% of global emissions. Malmodin et al. (2010), Malmodin and Lundén (2016) estimated the ICT and entertainment & media sectors in Sweden produced 1.3% of global CO_2 emissions in 2007, which peaked at around 2010 owing to the increasing use of tablets and smartphones instead of PCs and TVs. Zhang and Liu (2015) investigated the impacts of ICT industry on China's regional carbon emissions, concluding that the reduction effects of ICT on CO_2 emissions varied with regions. Belkhir and Elmeligi (2018) provided a rigorous study on the global carbon footprint of ICT sector, revealing that the emission contribution of ICT sector would roughly double from 1 to 1.6% in 2007 to 3–3.6% by 2020. These studies have the merit of advancing our knowledge about the extent to which ICT sector affects carbon emissions. However, one major limitation of them is that they have not revealed how economic activities related to ICT sector (e.g. industrial linkage, production and consumption patterns change) drive carbon emissions (Joyce et al., 2019). This may lead to a false perception that mitigating carbon emissions only requires specific carbon reduction actions within ICT sector without economy-wide adjustment and optimization. As such, it is difficult to formulate practical and effective economic policies for sustainable ICT development.

To fill the above-mentioned gaps, this paper attempts to explore the embodied carbon impacts of ICT and their associated mechanism at the sector level, which are crucial for allocating sectoral carbon responsibilities in the agenda of climate change mitigation (Wang et al., 2018). To achieve this goal, we develop an embodied carbon analysis framework for ICT sector by integrating input-output analysis approaches. Compared with econometric approaches, the input-output approaches, i.e. subsystem analysis, structural path analysis, and structural decomposition analysis, are proven useful in tracking both consumption-based emissions of specific economic sectors and the exchanging mechanisms of carbon flows between sectors (Yang and Chen, 2014; Gemechu et al., 2012; Egilmez et al., 2013; Zhou et al., 2018a; Jiang and Liu, 2015). We first perform an input-output analysis to assess the embodied carbon emissions of ICT sector and its subsectors,[1] and then examine the carbon flows between ICT and non-ICT sectors using a subsystems analysis. We further conduct a structural path analysis to uncover how carbon emissions accumulate along detailed ICT supply chains. Finally, we adopt a structural decomposition analysis to determine how economy-wide production and demand factors drive ICT embodied emissions change. Based on the proposed framework, we conduct a case study for China's ICT sector, which has witnessed remarkable expansions over the past few decades and formed a cluster of interlinked industries (see Section 3).

This study aims to extend existing studies in the following ways. First, we investigate the embodied carbon emissions of a cluster of ICT subsectors from the perspectives of impacts and mechanism, both of which are essential for a comprehensive understanding of the sector-level carbon implications of ICT and meaningful for formulating practical carbon management measures of ICT. Second, we develop an embodied carbon analysis framework for ICT sector by integrating input-output analysis approaches. With the framework, we can not only assess the consumption-based carbon emissions of ICT sector, but also identify their source sectors, transfer paths, and economic drivers. The framework can also be applied to explore carbon management potentials for other economic sectors with high indirect carbon emissions such as construction and services sector. Third, we complement existing studies with empirical evidence from China, where ICT sector has been directed few environmental concerns and carbon regulations. The empirical results of this study will help provide early warnings of ICT-related carbon emission issues for China's policymakers.

The rest of this paper is organized as follows. Section 2 illustrates the integrated embodied carbon analysis framework and presents detailed input-output models related to the framework. Section 3 describes the case study selection and data. In Section 4, we apply the framework to investigate the embodied carbon emissions of China's ICT sector and present the empirical results. Section 5 concludes the study.

2. Methodology

2.1. Integrated framework for embodied carbon analysis

This study developed a framework for investigating the embodied carbon emission impacts of ICT sector and their associated mechanism by integrating several input-output analysis approaches. Fig. 1 shows the technical process of integrating input-output analysis (IOA), subsystems analysis (SA), structural path analysis (SPA), and structural decomposition analysis (SDA) in the framework.

The first step of ICT embodied carbon emission modeling is to construct a production-based sectoral emission inventory that estimates the direct carbon emissions from fossil fuel combustion and

[1] According to the Industrial Classification for National Economic Activities (GB/T 4754-2017) in China (NBSC, 2017a), ICT sector is mainly constituted by two branches: ICT manufacturing sectors (i.e., computer, communications and other electronic equipment manufacturing) and ICT services sectors (i.e., information transmission, software and information technology service). The two ICT clusters can be further divided into corresponding subsectors based on the classification. The details of the sector coverage are given in Section 3.

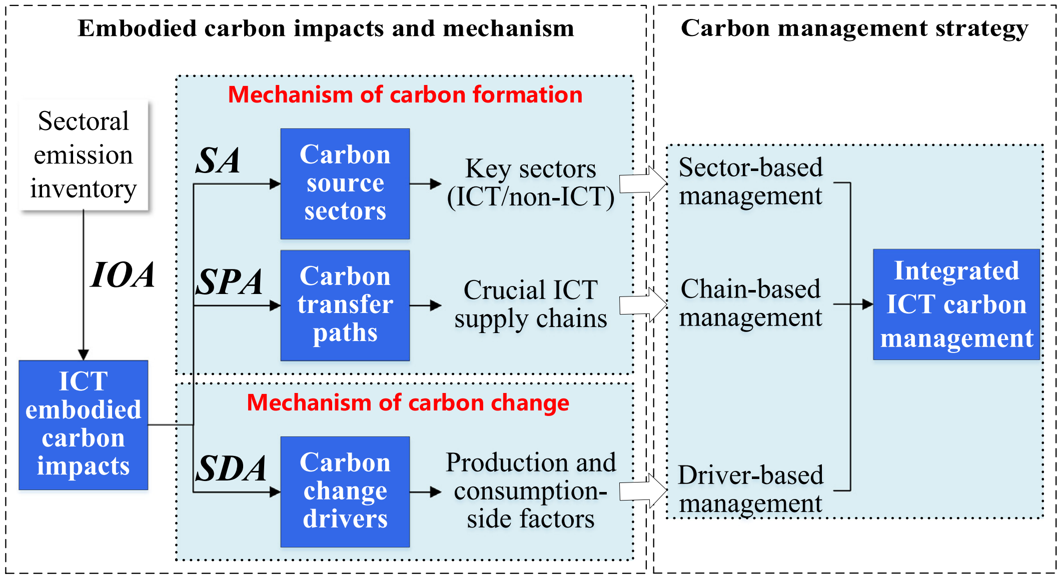

Fig. 1. An integrated embodied carbon analysis framework for ICT sector. IOA: input—output analysis. SA: subsystem analysis. SPA: structural path analysis. SDA: structural decomposition analysis.

industrial processes associated with economic sectors. Based on the emission inventory, IOA is used to calculate the embodied emissions of ICT sector and its subsectors using the consumption-based accounting principle (Davis and Caldeira, 2010).

To identify the main source sectors of ICT embodied emissions, SA is applied to identify the carbon emission roles played by ICT sector (direct impacts) and non-ICT sectors (indirect or induced impacts). In parallel, SPA is applied to examine how indirect carbon emissions transfer from major source (non-ICT) sectors to ICT sector through crucial ICT supply chains (or carbon transfer paths). Combining SA and SPA reveals the mechanism by which ICT embodied emissions accumulate from a consumption-based perspective, uncovering how ICT consumption activities induce carbon emissions through crucial ICT supply chains, and eventually from the source sectors. Given that ICT sector is mostly driven by cost-efficiency and economic policy in recent decades (Atkinson and Mckay, 2007), SDA is applied to analyze the carbon change drivers focusing on the economy-wide factors in relation to ICT, e.g., production efficiency and demand level. The SDA results show the mechanism of ICT embodied emissions change from an economic perspective.

Integrating these IOA approaches into the embodied carbon analysis framework provides abundant useful insights into how ICT sector contributes to the total carbon emissions and how major carbon sources, transfer paths, or economic drivers affect ICT embodied emissions. This allows the derivation of an integrated ICT carbon management strategy based on major source sectors, supply chains, and economic drivers. This strategy is promising for a systematic mitigation of embodied carbon emissions for ICT sector.

2.2. Models related to the framework

Measuring the embodied carbon emissions of ICT sector begins with the environmental input-output model, which considers the environmental impacts of economic activities from production and consumption perspectives (Miller and Blair, 2009). The model can be expressed as[2]

$$x = (I-A)^{-1}y = Ly \tag{1}$$

where $x = (x_i)_{n\times1}$ is a vector of sectoral output; $A = (A_{ij})_{n\times n}$ is the direct consumption coefficient matrix with elements $A_{ij} = Z_{ij}/x_j$; $L = (I-A)^{-1} = (L_{ij})_{n\times n}$ is the Leontief inverse matrix; and $y = (y_j)_{n\times1}$ is the final demand vector. With reference to carbon emissions studies, the aggregate CO_2 emissions generated by production sectors can be formulated as

$$C = fx = fLy \tag{2}$$

where f is a row vector of CO_2 emission intensity with elements $f_i = C_i/x_i$, and C_i is the direct CO_2 emissions generated by sector i and $C = \sum_i C_i$.

Then, the embodied CO_2 emissions in the final demand of ICT subsectors can be formulated as

$$EC^I = fL\hat{y}^I \tag{3}$$

where EC^I is a row vector containing only the embodied carbon emission columns of ICT subsectors, with zeros elsewhere; $\hat{y}^I$ is the diagonal matrix of final demand vector y^I, which contains only the elements of ICT subsectors with zeros elsewhere.

ICT can be considered as a system of general-purpose technologies and industries (Røpke, 2012). As such, a subsystem analysis (SA) approach is applied to examine the embodied emission roles played by different ICT subsectors and uncover their interactions with non-ICT sectors. Following Alcántara and Padilla (2009) and Butnar and Llop (2011), the CO_2 emissions embodied in ICT subsectors can be attributed to two mutually exclusive components:

$$\begin{aligned} ExC &= f^N(A_{NN}L_{NI} + A_{NI}L_{II})y^I \\ InC &= f^I(A_{IN}L_{NI} + A_{II}L_{II} + I)y^I \end{aligned} \tag{4}$$

where ExC are the emissions generated by non-ICT sectors due to ICT subsectors' purchasing activities; and InC are the emissions generated within ICT subsectors. In this model, ICT subsectors are extracted from the economic system to constitute an ICT subsystem, while the remaining sectors constitute a non-ICT subsystem. Correspondingly, the CO_2 emission intensity vector f, the direct consumption coefficient matrix A, and the Leontief inverse matrix L are all divided according to their elements belonging to ICT subsectors and non-ICT sectors, denoted by the subscripts and superscripts I and N, respectively. Detailed discussions

[2] We use the competitive imports assumption here, as we consider only the CO_2 emissions of China's ICT sector in this study. This assumption has the advantage of approximately estimating the emissions embodied in sectoral consumption activities. A detailed discussion on the differences between the competitive and non-competitive imports assumption can be found in Su and Ang (2013).

on the derivation of carbon emission components in Eq. (4) are given in Appendix A.

To reveal the mechanism of how carbon emissions are transferred along individual ICT supply chains, a structural path analysis (SPA) approach is involved in this study. Using the Taylor series approximation to expand the Leontief inverse (Lenzen, 2003), the embodied carbon emissions of ICT sector in Eq. (3) can be rewritten as a summand of different emission layers:

$$EC^I = fI\hat{y}^I + fA\hat{y}^I + fA^2\hat{y}^I + fA^3\hat{y}^I + fA^4\hat{y}^I + \ldots, \tag{5}$$

where $fA^t\hat{y}^I$ represents the contribution of CO_2 emissions from the t th ICT production tier. For instance, assuming the case where $\hat{y}^I$ is the demand for computers, $fI\hat{y}^I$ is the direct CO_2 emissions generated by the computer companies (e.g., from fossil fuel combustion) in the computer assembly phase (the zeroth tier). To produce the computer, companies need to purchase computer parts and accessories ($A\hat{y}^I$), e.g., screen, memory, and processing units, from their upstream suppliers and these suppliers emit $fA\hat{y}^I$ CO_2 in the processes of manufacturing the required parts or accessories (first tier). In turn, the computer part suppliers also need to purchase raw materials ($A^2\hat{y}^I$), e.g., glasses, metals, and chemicals, and thus $fA^2\hat{y}^I$ CO_2 emissions are released in the production of the materials (second tier). And so on and so forth, the process continues similarly for all production tiers.

The nodes (companies or sectors) in successive production tiers constitute a complete supply chain or carbon transfer path (Skelton et al., 2011; Oshita, 2012; Owen et al., 2016; Liu et al., 2018a). For example, $f_k a_{kj}a_{jl}a_{li}\hat{y}^I{}_i$ is a third-tier path, which denotes the emission path $k \rightarrow j \rightarrow l \rightarrow i$. In general, there are n paths in the zeroth tier, $n \times n$ paths in the first tier, and $(n \times n)^2$ paths in the second tier and the number of paths increases exponentially with each tier. Furthermore, crucial emission paths can be identified by scanning the carbon emissions associated with the main supply chains.

To evaluate the major economic drivers for the temporal changes in the carbon emissions embodied in ICT sector, we involve a structural decomposition analysis (SDA) approach in this study (Peters et al., 2007; Guan et al., 2008; Feng et al., 2015; Chen and Chen, 2017). There are two commonly used decomposition techniques in SDA: the D&L method (Dietzenbacher and Los, 1998) and the logarithmic mean Divisia index method (Ang et al., 2003; Ang, 2005; Su and Ang, 2012). We adopt the D&L method to conduct SDA in this study. Based on Eq. (3), five driving factors related to ICT embodied emission changes (ΔEC^I) can be identified: sectoral emission intensity (f), production structure (L), domestic final consumption of ICT (y^I_c), capital investment in ICT (y^I_i), and ICT export y^I_e. The changes of the carbon emissions embodied in ICT sector can be decomposed as:

$$\Delta EC^I = \Delta fLy^I + f\Delta Ly^I + fL\Delta y^I_c + fL\Delta y^I_i + fL\Delta y^I_e \tag{6}$$

where $y^I = y^I_c + y^I_i + y^I_e$, and ΔfLy^I shows the contribution of variations in sectoral emission intensity; $f\Delta Ly^I$ shows the contribution of variations in intermediate production structure; $fL\Delta y^I_c$ shows the contribution of variations in domestic ICT consumption; $fL\Delta y^I_i$ shows the contribution of variations in ICT capital investment; and $fL\Delta y^I_e$ shows the contribution of variations in ICT export volume. To address the non-unique issues in SDA, we take the mean of all possible first-order decompositions to derive each factor's contributing value (Dietzenbacher and Los, 1998).

3. Case selection and data

We use China as a case study to investigate how ICT sector drives carbon emissions. As the largest developing country in the world, China has experienced rapid growth in both ICT sector and CO_2 emissions over recent decades. As is shown in Fig. 2, China's ICT sector has experienced a spectacular growth in gross output over 1995–2015, with an over seventeen-fold increase from 158 billion euros to 2789 billion euros (Montserrat et al., 2018). During this same period, China's CO_2 emissions from fuel combustion and industrial processes (e.g. cement production) have exceeded 10 Gt, increasing by more than three times (Olivier et al., 2016). In 2015, China ranked first worldwide in terms of both the gross output of ICT sector and CO_2 emissions, making up 36.6% of global ICT output and 29.5% of global emissions. Given these statistics, promoting the low-carbon development of ICT sector in China would greatly contribute to worldwide green ICT initiatives and the global carbon abatement agenda (Gao et al., 2019).

Moreover, mitigating carbon emissions associated with ICT sector is increasingly significant for China in recent years. First, ICT sector were select as one of the strategic emerging industries in China's 12th Five-Year Plan (2011–2015) (NDRC, 2011). Massive investment in ICT sector has boosted it become a large industry involving many sub-sectors. As Table 1 lists, China's ICT sector is composed by a set of correlated subsectors. Second, China has become the world's largest producer of ICT products since 2006, which produced 80% of PC, 77% of phone handset, 50% of color TV for the world in 2016 (Simon, 2014; NBSC, 2017b). China is also the largest potential market of ICT products and services in the world, due to its largest population and fast economic growth (Sanou, 2017). The massive production and consumption of ICT would cause large amounts of electricity and resources consumption, and resultant CO_2 emission in the future. Third, the ongoing advancement in ICT is ever changing the ICT production and consumption patterns, and therefore inducing considerable changes in the embedded emissions of ICT sector. For instance, the emergence of 3G technologies in China has fundamentally transformed the supply chain of telecommunication industry since 2008 (Fettweis and Zimmermann, 2008). The increasingly complicated mobile communication equipment and its supply chain might have more and more embedded emissions. In view of the above circumstances, a comprehensive understanding of the carbon emissions of ICT sector is imperative for China's policymakers while formulating sectoral emission reduction policies. Therefore, we select China as a typical case to trace how ICT sector drives carbon emissions.

The data used in this study mainly include 2002–2012 monetary input-output tables (IOTs) and sectoral CO_2 emission inventory for China. We obtain China's IOTs in current price from the Chinese National Bureau of Statistics (NBSC) for 2002 with 122 sectors, for 2007 with 135 sectors, and for 2012 with 139 sectors (NBSC, 2006, 2009, and 2015). The three IOTs are then harmonized into a consistent sector classification with 105 industrial sectors. For the simplicity of illustration, the empirical results are presented in a more aggregated form, with 7 ICT subsectors (I1-I7) and 21 non-ICT sectors (N01-N21). Detail of the 28-sector classification is given in Appendix B.

We further obtain the primary sectoral CO_2 emission inventory data in 2002, 2007, and 2012 from Pan et al. (2017), in which direct CO_2 emissions of 48 economic sectors originating from both fuel combustion and industrial processes were estimated using up-to-date revised official data based on IPCC guidelines (IPCC, 2006) and China National Greenhouse Gas Inventory 2005 (NDRC, 2014). In particular, with regard to the ICT services sectors, whose energy consumption data were not available, we estimate their direct energy consumption and CO_2 emissions by using a treatment approach of transaction weight-shares (Su et al., 2010). We then apply the "Data Treatment Scheme 2" proposed by Su et al. (2010) to generate the CO_2 emission dataset that matches the detailed 105-sector classification in the IOTs.

To perform the SDA, we adjust the 2007 and 2012 IOTs to 2002 constant prices using the double-deflation method (United Nations, 1999). Sector-level price indices, collected from the China Price Statistical Yearbook (NBSC, 2013), are used to deflate the monetary IOTs. The producer price indices (PPI) are used to deflate the agriculture sectors and industrial sectors. The construction and installation indices, retail price

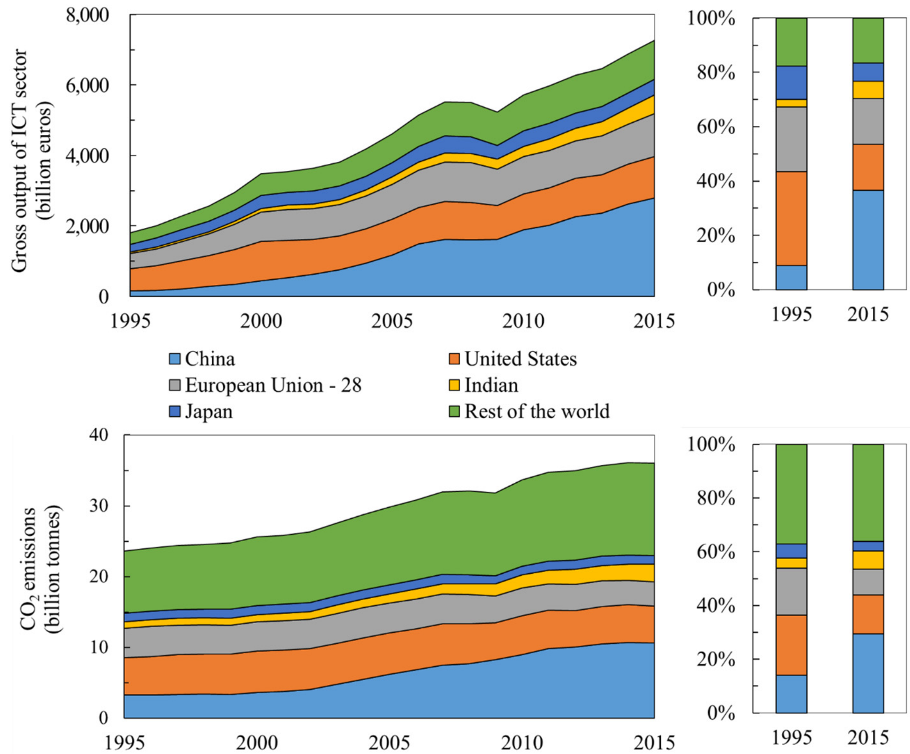

Fig. 2. The growth of ICT sector and CO_2 emissions in major economies over 1995–2015. Note: The time-series data of the gross output of ICT sector and CO_2 emissions are collected from the "2018 PREDICT Dataset" (Montserrat et al., 2018) and a global CO_2 emissions report (Olivier et al., 2016), respectively.[a] [a]These data are both published by the EU Commission's Joint Research Centre. The PREDICT database covers 28 EU countries and 12 other major countries in the world for the period from 1995 to 2017.The CO_2 emissions report calculates the CO_2 emissions from fossil fuel use and cement production for 208 countries and regions in 1970–2015.

indices, and consumer price indices (CPI) are used for the construction, wholesale and retail, and services sectors, respectively. In particular, electronic equipment indices are used for deflating ICT manufacturing sectors (I1-I5) and communication service indices are used for ICT services sectors (I6-I7). The deflators (involving 46 sectors) are then mapped to the 105 sectors in the IOTs.

Table 1
Subdivision and specification of China's ICT sector.

Sector clusters	Sector specification
ICT manufacturing	
Computer	Manufacture of computer (overall unit, parts, and peripheral), industrial control computer, and information security equipment
Communication equipment	Manufacture of communication system equipment and communication terminal equipment
Audio-visual apparatus	Manufacture of radio and television, radar, general audio-visual, and intelligent consumption equipment
Electronic components	Manufacture of electronic parts (semiconductor, integrated circuit, etc.) and components (electronic circuits, sensor, etc.)
Other ICT equipment	Manufacture of electronic physical equipment and other unspecified electronic equipment
ICT services	
Software and IT services	Software development and information technology (IT) services, Internet and related services
Telecommunication services	Telecommunications, radio and television services, and satellite transmission services

Note: The classification and specification of ICT sector is based on the Industrial Classification for National Economic Activities (GB/T 4754-2017) in China (NBSC, 2017a), which is consistent with China's official published statistics data such as China's national input-output tables and Statistical Yearbook of Electronic Information Industry.

4. Results and discussion

4.1. Embodied carbon emissions of ICT

Using Eq. (3), we calculated the embodied carbon emissions of China's ICT sector in 2002, 2007, and 2012. Table 2 shows the comparison between the direct carbon emissions (DCEs) and embodied carbon emissions (ECEs) of ICT sector. As far as DCEs is concerned, ICT appears to be a carbon-friendly sector, generating approximately 7 Mt CO_2 emissions in 2012. This figure, however, might create an incorrect impression for policymakers that emission mitigation policies are not necessary for ICT sector, because it appears not to be a significant direct emission contributor.

However, the ECEs of ICT sector tell a very different story. The ECEs are significantly higher than the DCEs, for both the whole ICT sector and the subsectors. For example, the ECEs of *software and IT services* sector are more than 400 times the DCEs (see Table S2 in Appendix B). The total ECEs of ICT sector accounted for more than 4% of China's total emissions in 2012. This proportion is approximately twice as previous estimates (around 2%) for the global ICT sector (GeSI, 2015; Belkhir and Elmeligi, 2018). The reason for this inconsistency may be methodological or empirical. On the one hand, the input-output analysis approach adopted in this study considers the circular carbon emissions embodied

Table 2
Direct and embodied carbon emissions of ICT sector in 2002–2012.

Year	DCEs		ECEs		Gaps (ECEs - DCEs)
	Mt CO_2	% total emissions	Mt CO_2	% total emissions	
2002	10	0.3	145	3.9	135
2007	12	0.2	318	4.6	306
2012	7	0.1	357	4.1	350

in ICT supply chains. As such, it provides a more rigorous estimate of the comprehensive carbon impacts of ICT compared to the LCA approach. On the other hand, high-carbon electricity generation in China, driven by a heavy reliance on coal-fired power,[3] also contributes to the higher proportion of ICT sector with respect to carbon emissions. As an electricity-hungry sector, ICT sector generates much more carbon emissions in China compared to developed countries while consuming the same amounts of electricity.

Despite disparities across studies, it would be safe to conclude that ICT sector is associated with intensive embodied emissions in China. ICT sector became the fifth leading embodied emission sector in 2012, ranking only after *construction*, *services*, *transport equipment*, and *special-purpose machinery* (see Fig. S1 in Appendix B). To effectively promote emission reduction in relation to ICT, it is more reasonable to formulate ICT carbon management measures based on embodied emissions, rather than direct emissions.

When looking at subsector roles, the *computer* and *communication equipment* sectors are the two major contributors, which together comprised nearly half of the ECEs of ICT sector in (see Fig. 3). This is a high proportion, considering that even more energy would also be consumed during the use of computer and communication equipment. These end-use device manufacturing sectors induce significant carbon emissions through their numerous supply chains, and therefore have high embodied carbon content. Meanwhile, the role of the remaining sectors must also be considered. All these sectors, excluding the *other ICT equipment* sector, contribute more than 10% to the total emissions of ICT sector. These results highlight the heterogeneous roles of ICT subsectors, suggesting the possible effectiveness of sector-specific emission reduction policies.

Focusing on the changing trends over the study period, China's ICT sector experienced a decline of 29% in DCEs and an increase of 139% in ECEs. DCEs and ECEs show the opposite change trajectories, highlighting an increasing gap between the direct and embodied emissions of ICT sector (see Table 2). In terms of temporal trends, we can easily figure out that more than 150% of the total decrease in DCEs and less than 20% of the increase in ECEs happened in 2007–2012. It appears considerable emission reduction achievements regarding both DCEs and ECEs have been made around 2007. After that, a significant decline in DCEs occurred and the fast growth in ECEs plateaued.

We can offer an intuitive explanation for the changing trends in embodied carbon emissions by dividing ICT sector into two categories: ICT manufacturing and ICT services. As is depicted in Fig. 3, the ECEs in ICT manufacturing sectors significantly increased in 2002–2007, then remained steady in 2007–2012. In particular, we observe that the ECEs of the *computer* sector peaked around 2007. Meanwhile, ICT services sectors (e.g. *software and IT services*) contributed to almost the entire increase in total ECEs in 2007–2012. Although ICT manufacturing sectors dominated the ECEs, the share of ICT services sectors increased from 13% to 22% in 2002–2012. These results suggest a significant transition occurred within ICT sector around 2007; however, further analysis of these factors is needed.

When re-examining the embodied carbon emissions from an economic perspective, we observe the heterogeneous carbon intensity (measured by embodied emissions per unit output) among ICT subsectors. As is shown in Fig. 4, ICT device sectors such as *communication equipment* and *audio-visual apparatus* are more carbon-intensive than ICT services sectors such as *software and IT services* and *communication services*. This suggests that ICT service sectors should be prioritized more than ICT device sectors when designing sustainable ICT policies (Zhou et al., 2018a). In addition, the carbon-intensity of *electronic components* is much lower than the intensity of other devices sectors. This is because the products of this sector have relatively simple functionality, which may

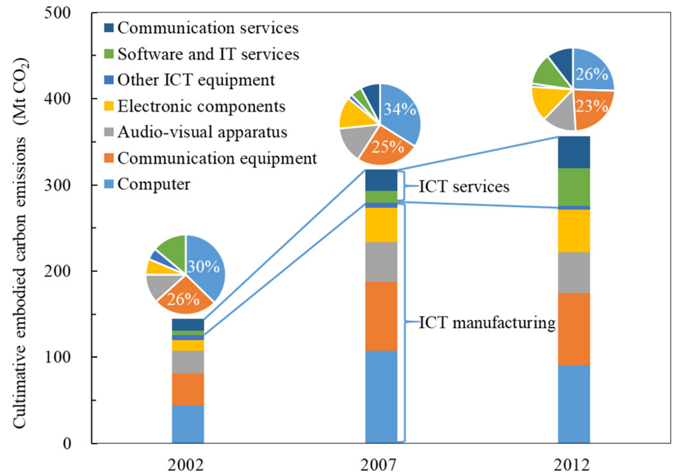

Fig. 3. Changing trends of carbon emissions embodied in ICT subsectors over 2002–2012. Note: Pie charts show the proportion of ICT subsectors with respect to total embodied emissions. The blue lines mark the respective changes of carbon emissions embodied in the ICT clusters of manufacturing and services.

be a major factor driving the use of more energy materials (Williams, 2011).

The embodied carbon intensity of ICT sector remained steady in 2002–2007, but then decreased significantly in 2007–2012, showing an opposite changing trend in comparison to the volume indicator. These changes may explain the plateaued ECEs in the second subperiod. Meanwhile, the decreasing embodied intensity suggest that ICT sector is more beneficial to the intensity target than to the quantity target of China's "double control" carbon strategy (Zhang et al., 2019). However, a more detailed analysis of the economy-wide factors is needed. The structural decomposition analysis in Section 4.3 explores the major economy-wide factors driving the changes in ICT embodied emissions. Nevertheless, ICT sector appears to be developing in a more sustainable direction from an economic perspective.

4.2. Sources and paths of ICT embodied carbon emissions

To track the formation mechanism of the ICT embodied emissions, this section explores a subsystem analysis and structural path analysis. The subsystem analysis is used to identify the main source sectors resulting in carbon emissions for ICT sector from a carbon flow perspective. The

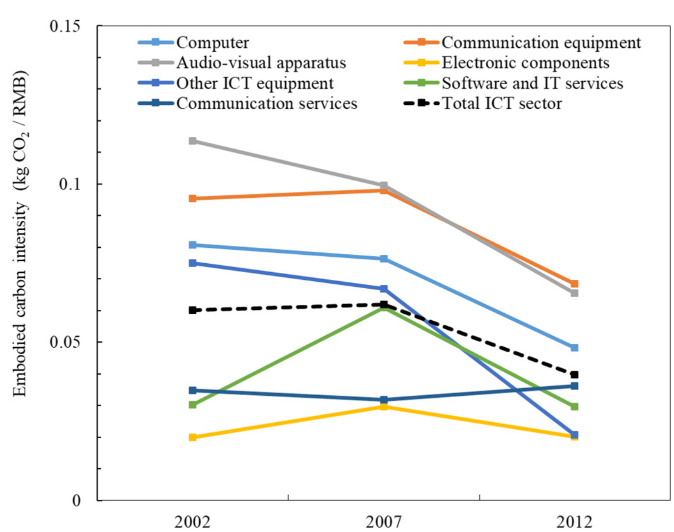

Fig. 4. Changing trends of the embodied carbon intensity of ICT subsectors over 2002–2012.

[3] In 2012, coal-fired power accounted for 75% of China's total electricity generation. By contrast, the proportion was only 39% as for the world (World Bank, 2012).

Table 3
Attribution of the carbon emissions embodied in ICT sector in 2012 (unit: Mt CO_2).

ICT industrial clusters	External carbon component	Internal carbon component	Embodied carbon emissions
Computer	89.6	1.4	91.0
Communication equipment	82.8	1.0	83.8
Audio-visual apparatus	46.7	0.6	47.3
Electronic components	48.6	0.6	49.2
Other ICT equipment	4.3	0.0	4.4
Software and IT services	43.6	0.4	44.0
Communication services	36.1	1.1	37.2
Total ICT sector	351.7	5.1	356.8

structural path analysis reveals how carbon emissions transfer through crucial supply chains (or transfer paths) to ICT sector.

4.2.1. Main source sectors

Table 3 summarizes the subsystem analysis results generated from Eq. (4). The embodied carbon emissions of ICT sector can be attributed to two mutually exclusive components: external emissions generated in production by non-ICT sectors to satisfy ICT subsector demand, and internal emissions generated in production by ICT subsectors to satisfy their own demand.

By comparing the external and internal components, we find that over 95% of the carbon emissions embodied in ICT sector could be attributed to the production processes associated with non-ICT sectors. In contrast, production within ICT subsectors played a much smaller role. The large divergences between the two emission components are somewhat unexpected; however, they demonstrate the significance of analyzing upstream (or source) sector roles in driving ICT embodied emissions. From this perspective, the production within ICT sector contributes little to the increase of embodied emissions, while the production in upstream sectors is decisive. This is because ICT sector can induce large amounts of indirect emissions by consuming intermediate products from these non-ICT sectors.

We depicted Fig. 5 to explore the most significant source sectors driving ICT embodied emissions from the perspective of carbon flows. This Sankey diagram clearly presents the inter-industrial carbon flows between major source sectors and ICT subsectors in 2012.

From the carbon flow source perspective, several upstream sectors explain most of the embodied carbon emissions of ICT, including *electricity* (*189 Mt*), *metals smelting and pressing* (*36 Mt*), *chemicals* (*33 Mt*), *nonmetal mineral products* (*33 Mt*), and *transport* (*24 Mt*). Of these, *electricity* is the largest emission source sector, transferring more than half of the total embodied emissions to various ICT subsectors. Therefore, reducing the carbon emissions generated in electricity production is significant for mitigating carbon emissions embodied in ICT sector. *Metals smelting and pressing*, *chemicals*, and *nonmetal mineral products* are the other three significant emission source sectors, together transferring approximately 30% of the total emissions to ICT sector. Given these results, improving the carbon performance of these basic material sectors may be an efficient way to reduce embodied emissions for ICT sector. As a kind of carbon-intensive infrastructure services, *transport* is also a considerable emission source for ICT subsectors. This indicates that mitigating emissions in the *transport* sector is vital for green ICT. Identifying these sectors suggests that sector-specific emission reduction policies targeting major source sectors can have significant impacts (Sun et al., 2019).

From the carbon flow destination perspective, both ICT manufacturing and ICT services sectors induced large amounts of carbon emissions from the electricity sector. This is not only because the production and operation of ICT products and services requires electricity consumption, but also because the production of materials and components for ICT products is electricity dependent. There are much larger carbon flows between the three basic material sectors and ICT manufacturing sectors compared to the ICT services sectors, as ICT devices and equipment require more intermediate inputs from these material sectors. The products of these sectors are generally carbon-intensive; as such, ICT manufacturers could use other low-carbon materials as inputs to reduce embodied emissions.

To analyze the changing roles of source sectors in 2002–2012, we plot the detailed ICT embodied emissions sourced from all non-ICT sectors in Fig. 6. The figure shows that several sectors have transferred increasingly large amounts of carbon emissions to ICT sector over the study period. Among the sectors, *electricity* (*N18*) showed the most significant growth in transferring carbon emissions to ICT sector. Therefore, production and use of clean electricity is the most effective way to reduce the embedded emissions of ICT sector. Meanwhile, the greater role of *chemicals* (*N8*), *metals smelting and pressing* (*N10*), and *transport* (*N20*) should be highlighted. Limiting electricity or basic raw material

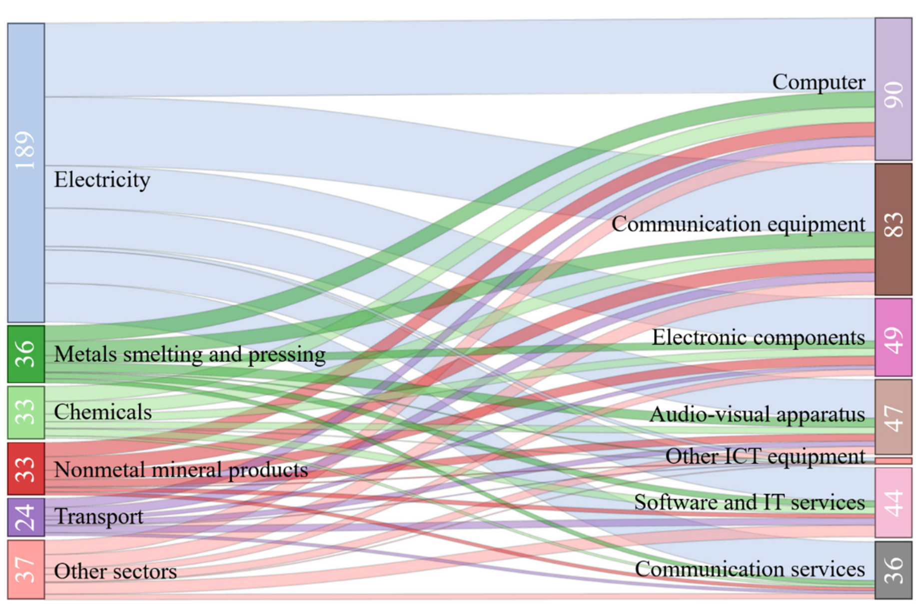

Fig. 5. Carbon flows between major source sectors and ICT subsectors in 2012 (unit: Mt CO_2).

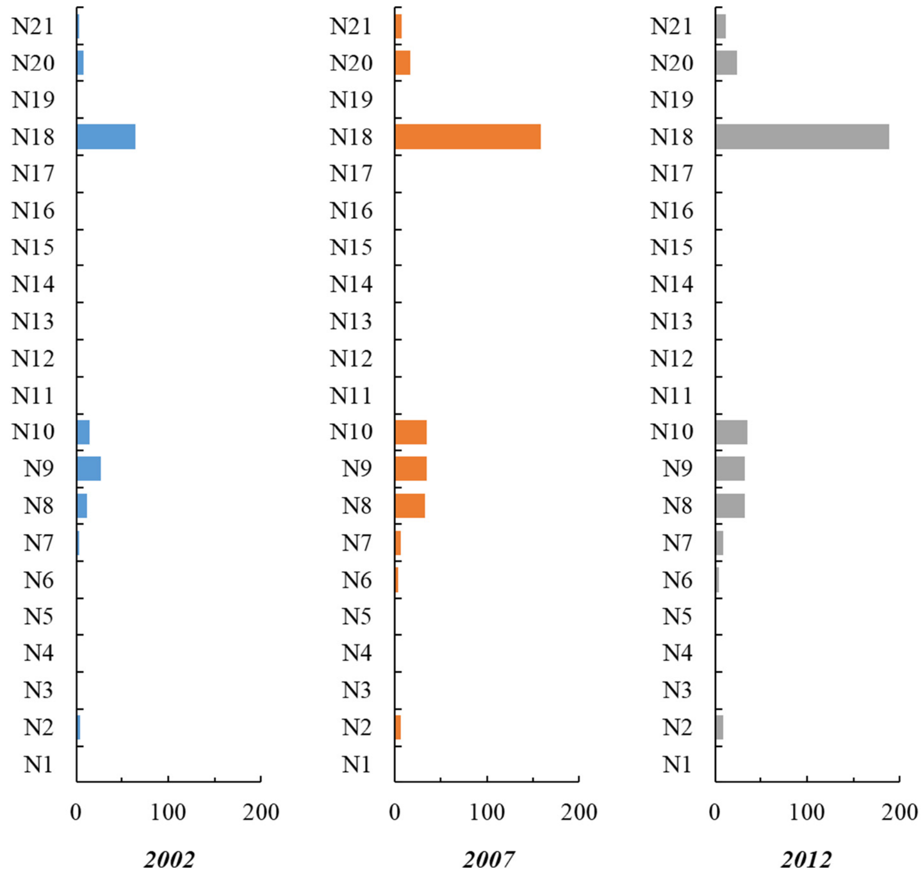

Fig. 6. Changing trends of embodied carbon flows from source sectors to ICT sector in 2002, 2007, and 2012 (unit: Mt CO_2).

consumption from these sectors should be a key focus for mitigating emissions embodied in ICT sector. Other sectors have also emerged as considerable sources of embodied emissions, i.e. *construction* (*N21*), *mining and dressing* (*N2*), and *petroleum processing and coking* (*N7*). In general, the changing trends of embodied emissions from source sectors remind us to formulate carbon regulatory policies for several significant emission sources, and to curb the carbon emission growth from emerging source sectors.

4.2.2. Crucial transfer paths

ICT can directly or indirectly induce carbon emissions through its complex supply chains. As such, identifying critical carbon transfer paths provides valuable insights for supply chain-wide carbon management (Zhou et al., 2018b). Table 4 shows the results of applying Eq. (5) to derive the carbon emissions embodied in different ICT production tiers in 2012. The column marked "production tier" shows the number of industrial sectors involved in ICT supply chains. For example, "Tier 2" ICT production involves two industrial sectors in its supply chains, and the carbon transfer path can be expressed as "sector1 → sector2 → ICT". When the number is zero, it means that the supply chains in this production tier have no industrial sector. This represents the direct CO_2 emissions generated in ICT production processes. The column marked "effect on ICT embodied emissions" demonstrates the total contributions of the supply chains in specific production tiers to the carbon emissions embodied in ICT sector.

Table 4
Contributions of each production tier to carbon emissions embodied in ICT sector in 2012.

Production tier	Number of ICT supply chains	Effect on ICT embodied emissions	Average effect from a single chain
Tier 0	0	0.9%	–
Tier 1	686	15.5%	2.26×10^{-2}%
Tier 2	67,228	21.5%	3.20×10^{-4}%
Tier 3	6,588,344	19.5%	2.96×10^{-6}%
Tier 4	645,657,712	15.0%	2.32×10^{-8}%
Tier 5 → ∞	∞	27.6%	–

As is shown in Table 4, emissions in Tier 0, representing the direct emissions generated by ICT sector, only account for 0.9% of the ICT embodied emissions. The contributions of the production tiers to ICT embodied emissions from Tier 1 to Tier 4, in turn, are 15.5%, 21.5%, 19.5% and 15.0%. The fifth or higher tier of industrial supply chains, accounted for 27.6% of the total ICT embodied emissions. These results show that 99.1% of CO_2 emissions of ICT sector came from circulatory intermediate consumption in different supply chain layers. Hence, analyzing crucial supply chains provides critical insights for mitigating ICT carbon, as these chains can greatly affect ICT embodied emissions through inter-industrial transactions.

To explore how carbon emissions transfer through different layers of ICT supply chains, we have drawn Fig. 7 to examine the distribution features of carbon transfer paths. As Fig. 7 depicts, carbon emissions are transferred from major source sectors to ICT subsectors through different supply chain tiers. Tier 1 supply chains, meaning the direct energy or material supply for ICT sector, contributed approximately 20% to the total embodied carbon emissions. In contrast, the indirect supply chains (second or higher tiers) contributed the major part of embodied emissions. This suggests the need for a carbon management strategy oriented to multi-layer supply chains.

There are significant differences in carbon transfer paths among sectors. For carbon source sectors, the electricity sector transfers more carbon emissions through the fifth or high tiers of supply chains; the basic material sector (metal, chemicals, and nonmetal) tends to transfer emissions through the second or third supply chain tiers; and the transport and other sectors mainly transfer emissions through the lower tiers

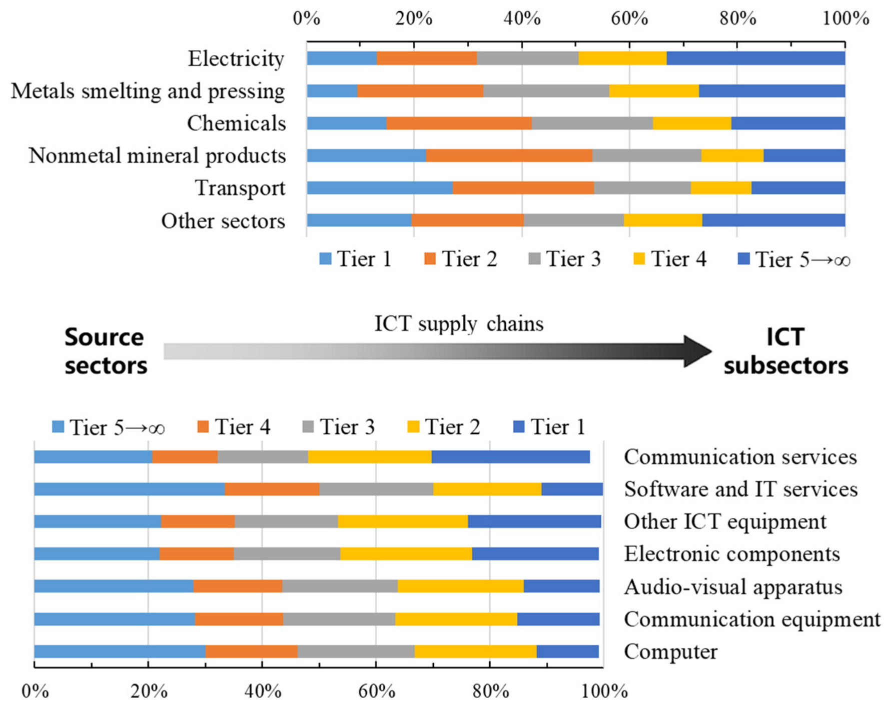

Fig. 7. Distribution of embodied carbon transfer paths by ICT supply chain tiers in 2012.

of supply chains. For ICT subsectors, the embodied carbon emissions of *electronic components*, *other ICT equipment*, and *communication services* are mainly caused by low supply chain tiers, as they have relatively short chains. In contrast, the embodied emissions of sectors such as *computer*, *communication equipment*, *audio-visual apparatus* and *software and IT services* are concentrated mainly in Tier 2 and Tier 3. This suggests that the indirect inputs for these sectors appear to be highly carbon-embedded. Hence, emission reduction policies targeting different layers of supply chains are needed.

To identify the crucial transfer paths through which carbon flows from source sectors to final ICT products, we scan and rank individual supply chains. These chains start from the upstream production process, then proceed to the intermediate consumption of inputs, and eventually to the final demand for ICT products. For example, the path "Electricity → ICT" shows the CO_2 emissions generated in the production of electricity that is directly consumed by ICT sector, while "Electricity → ICT → ICT" shows the CO_2 emissions generated in the production of electricity that is indirectly consumed by ICT sector through self-purchase within the sector. We focus primarily on the first fourth-tier supply chains (from Tier 0 to Tier 4).[4] Table 5 lists the top 20 ranking carbon transfer paths, which generate 139.5 Mt CO_2 emissions, representing 39.1% of the total embodied carbon emissions of ICT sector in 2012.

As can be figured out from Table 5, eleven of the top 20 paths start from the electricity sector. This confirms that this sector is the major source of embodied carbon emissions of ICT sector. The top five ranking paths were associated with *electricity*, indicating that large amounts of carbon emissions generated by electricity production flow to ICT sector, either directly or indirectly. As such, cutting down source emissions from the *electricity* sector might be the most effective way to mitigate ICT embodied emissions.

The sectors *chemicals*, *metals smelting and pressing*, and *nonmetal mineral products* were involved in approximately half of the top 20 ranking paths. This indicates that these sectors were critical transmission channels for embodied emissions. They used significant amounts of electricity to produce essential raw materials and ICT components, and thus built a bridge between the carbon-intensive *electricity* sector

[4] The number of supply chains in each production tier grows exponentially. As such, the average effect of a single supply chain on the embodied emissions of ICT sector declines significantly (see Table 4). The emissions in the fifth or higher tier totally represent a large part of the embodied emissions; however, we do not examine the effects of individual supply chains in these tiers since the average effect is rather small.

Table 5
The top 20 ranking carbon emission paths, starting with source production sectors and ending with ICT final demand in 2012.

Rank	Emissions (Mt CO_2)	Contribution	Tier	Path[a]
1	24.80	6.95%	1	Electricity → ICT
2	12.16	3.41%	2	Electricity → ICT → ICT
3	11.61	3.25%	4	Electricity → Electricity → Electricity → Electricity → ICT
4	11.38	3.19%	3	Electricity → Electricity → Electricity → ICT
5	8.08	2.27%	2	Electricity → Electricity → ICT
6	7.37	2.07%	1	Nonmetal mineral products → ICT
7	6.41	1.80%	1	Transport → ICT
8	5.49	1.54%	3	Electricity → Chemicals → Chemicals → ICT
9	5.33	1.49%	2	Nonmetal mineral products → ICT → ICT
10	5.28	1.48%	4	Electricity → Chemicals → Chemicals → Chemicals → ICT
11	5.16	1.45%	3	Electricity → Metals smelting and pressing → Metals smelting and pressing → ICT
12	4.94	1.38%	1	Services → ICT
13	4.90	1.37%	1	Chemicals → ICT
14	4.89	1.37%	4	Electricity → Metals smelting and pressing → Metals smelting and pressing → Metals smelting and pressing → ICT
15	4.45	1.25%	3	Chemicals → Chemicals → Chemicals → ICT
16	4.15	1.16%	3	Electricity → ICT → ICT → ICT
17	3.71	1.04%	2	Chemicals → Chemicals → ICT
18	3.19	0.89%	4	Chemicals → Chemicals → Chemicals → Chemicals → ICT
19	3.17	0.89%	0	ICT
20	3.04	0.85%	2	Electricity → Chemicals → ICT
Total	139.5	39.1%		

[a] This column shows that many carbon transfer paths repeatedly involve a specific sector, such as "Electricity → Electricity", "ICT → ICT", and "Chemicals → Chemicals". This is mainly because there are large amounts of self-purchased intermediate products within these sectors. For instance, the supply (grids) part of the electricity sector purchases a high-level of electricity from the production (plants) part. This results in significant carbon transfers within the sector (Pan et al., 2017).

and ICT sector. Sectors like *transport*, *services*, and *ICT* itself appeared in some crucial paths, in which these sectors directly transfer carbon emissions to ICT sector.

The different features of the critical paths that transfer carbon emissions suggest that emission reduction measures should be refined to specific ICT supply chains (Andrae et al., 2017). For long order paths, carbon emissions could be curbed by focusing on the headstream sectors. In contrast, reducing ICT sector's direct or indirect purchases would help reduce emissions from the short order paths.

4.3. Drivers of ICT embodied carbon emission changes

In Section 4.1, we assessed the embodied carbon impacts of ICT sector using a consumption-based accounting principle. In Section 4.2, we uncovered the mechanism of embodied carbon emission formation from an inter-industrial carbon flow perspective. To further investigate the mechanism of embodied carbon emission changes, we applied a structural decomposition analysis to identify the major driving factors behind the ICT embodied emission changes from an economic perspective, i.e. the production or demand-side driving factors (Wang et al., 2015). Within the structural decomposition analysis framework applied to emission studies, the production-side factors mainly include sectoral carbon efficiency that relies on production technological level of specific sectors and production structure that is determined by the intermediate input relationship among sectors, while the demand-side factors refer to the total final demand level, sectoral demand distribution structure, and final demand structure (Su and Ang, 2012; Mi et al., 2017). Identifying these factors could provide a comprehensive insight for better curbing the growth of carbon emissions by balancing production and demand.

We derive the contributions of major economic factors to the carbon emissions embodied in ICT sector using Eq. (6). As is shown in Fig. 8, the changes in ICT embodied emissions over 2002–2012 are driven by five factors in relation to ICT production: emission intensity, and production structure (production-side factors); or ICT final demand: ICT domestic consumption, ICT investment, and ICT export (demand-side factors). In general, it appears that 2007 was a turning point; after then, carbon emissions embodied in ICT sector plateaued. In both sub-periods, the changes in the ECEs of ICT depend on the race between the growth in final demand and improvements in production efficiency.

The embodied carbon emissions of ICT sector increased by 173 Mt CO_2 from 2002 to 2007, largely driven by the significant growth of ICT export volume (+243 Mt). Improvements in emission intensity offset nearly half of the increase (−126 Mt), while emissions reduction driven by changes in production structure was relatively low (−20 Mt). In 2007–2012, the carbon emissions embodied in ICT sector edged up by 39 Mt CO_2, due to the much smaller increasing effects of ICT export (+140 Mt). The slowing effects of ICT export could be explained by the loss of partial competitiveness in electronic products for China during the period (Liu et al., 2018b). Meanwhile, the accelerated improvements in the production structure counterbalanced the increase (−116 Mt); this was accompanied by the weakened reduction effect from improvements in emission intensity (−56 Mt).

ICT investment became the second largest driver in explaining the growth in ICT embodied emissions, with an increased contribution from +39 Mt in 2002–2007 to +66 Mt in 2007–2012. Given that the ICT industry was selected as a strategic emerging industry in China's 12th Five-Year Plan (2011–2015) (NDRC, 2011), the growth in ICT investments is expected to last a long time (Yang and Shi, 2018). This, in turn, influences the embodied carbon growth, highlighting the importance of guidelines to moderate the embodied carbon impact of ICT investment. Although the contribution of domestic ICT consumption was small (approximately +40 Mt) over the study period, ICT consumption may become a new carbon emission booster, as China is the largest potential market of ICT in the world (Sanou, 2017).

When looking at the emission reduction effects caused by production-side factors at the sector level, the *electricity* sector played a significant role in slowing the fast growth of ICT's embodied carbon emissions over 2002–2012 (see Fig. 9). Emission intensity improvement in electricity production contributed −119 Mt to the embodied carbon emissions of ICT sector, while structure optimization of electricity production contributed −20 Mt. The *nonmetal mineral products* sector significantly contributed to mitigating ICT embodied emissions in both two aspects: reducing emissions by 40 Mt through emission intensity improvement, and reducing emissions by 39 Mt through production structure optimization, respectively. The emission intensity improvement within ICT sector also saved 19 Mt CO_2 emissions; however, the ICT production structure change appeared to have little impact. Additional significant reductions in emissions came from improving production efficiencies in the sectors providing products such as *metal smelting and pressing*, *raw chemical products*, *transport*, and *services*. Primary energy sectors, such as *mining* and *petroleum*, could also reduce carbon emissions embodied in ICT (−10 Mt and −7 Mt), although the effects remained small.

The production-side results suggest that improving the production efficiency of upstream sectors remains the most effective measure to reduce CO_2 emissions from ICT. China has invested significant effort to improve the carbon performance and production structure of high-carbon industries, and achieved great achievements over the past 20 years (Liu et al., 2018a). These actions have contributed to the decrease in ICT embodied emissions. However, there remain huge opportunities for improvement in the carbon intensity of sectors such as *transport* and *metals smelting and pressing*. Therefore, further synergistic carbon reductions between ICT and these sectors are needed in the coming decades.

A sector-level attribution analysis for demand-side factors shows a complete picture of what happened within ICT sector in 2002–2012. ICT subsectors played different roles in the changes in China's ICT embodied emissions associated with demand-side effects (see Fig. 9). The *computer* sector accounted for 36% of the total increase in embodied carbon induced by export volume growth. The *communication equipment* and *electronic components* sector contributed 29% and 24% to embodied carbon, respectively. These three sectors combined to explain 89% of the embodied carbon increase caused by ICT export growth, indicating that ICT devices exports were the major source of embodied carbon growth. In the other two demand categories, *communication service* sector accounted for 57% of embodied carbon growth induced by ICT domestic consumption, while *software and IT service* sector was responsible for 56% of the embodied carbon growth generated by ICT investment.

The demand-side results demonstrate the evolution of overall ICT demand in China and the impacts of that demand on ICT embodied emissions. China exported an increasing number of ICT devices to the global market and became the world's largest producer of ICT devices

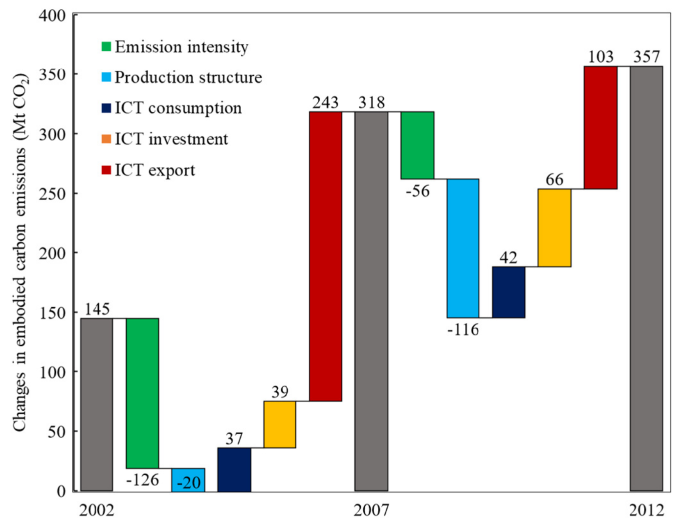

Fig. 8. Drivers of changes in carbon emissions embodied in ICT sector over 2002–2012.

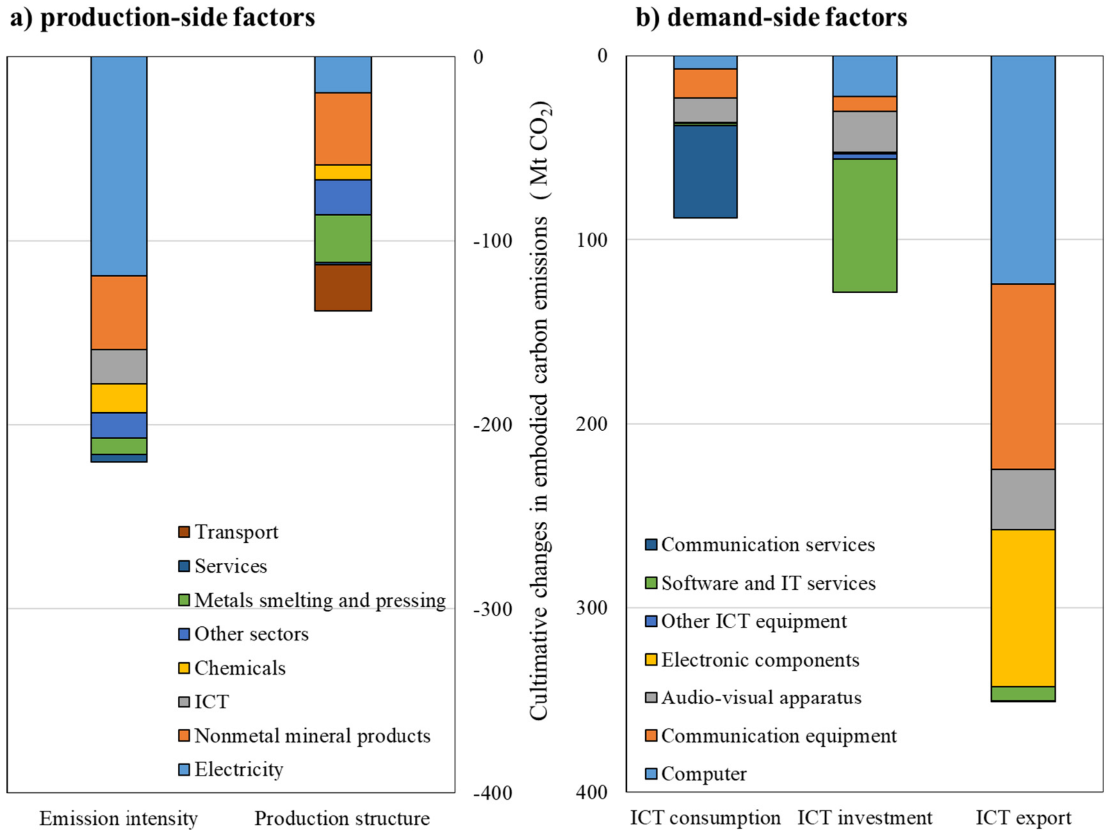

Fig. 9. Sector-level attributions of production (a) and demand-side (b) factors driving the embodied carbon emission of ICT sector changes over 2002–2012.

during 2002–2012 (Simon, 2014). For the domestic market, however, the maximum growth occurred in the ICT services domain. This is consistent with the ICT development process in China in the study period; this period marked an explosive growth of the Internet (Loo and Wang, 2017). With the introduction of the national information consumption policy (State Council, 2017), the carbon emissions embodied in ICT domestic consumption should become a major focus for ensuring sustainability.

5. Conclusions

Comprehensive understanding of the carbon implications of information and communication technology (ICT) is of great significance to formulating carbon management strategies in the new digital era. Increasing efforts have been made to investigate the carbon impacts of ICT products and development. However, few studies have addressed embodied carbon impacts of ICT sector and their underlying mechanisms. In this paper, we develop an embodied carbon analysis framework for ICT sector by integrating input-output analysis approaches. Through the framework, we derive a complete picture of carbon emissions embodied in ICT activities, manifesting not only the embodied carbon impacts of ICT sector but also the mechanisms of how upstream production sectors, supply chains, and production or demand-side factors affect the ICT embodied emissions.

Empirical results from China confirm that ICT sector is far more being environment-friendly while considering its embodied carbon impacts. ICT sector can induce significant amounts of carbon emissions through its requirement for substantial electricity and carbon-intensive materials as intermediate production inputs. Therefore, formulating carbon management strategies for ICT sector should be based on embodied rather than direct carbon emission indicators. For instance, it is reasonable to promote carbon footprint accounting and labeling of specific ICT products and services among business practitioner. The ICT embodied emissions varied greatly across ICT subsectors; ICT manufacturing sectors are more carbon-intensive, contributing most of the total embodied emissions. Hence, policymakers should prioritize the greener ICT service sectors when designing industrial development policies for ICT.

The most important sources and transfer paths of ICT embodied emissions were associated with China's industrial production sectors. The *electricity* sector and basic materials industries (*chemicals*, *metal smelting and pressing*, and *non-metal products*) were the most significant sources of carbon flows to ICT, contributing more than 80% of the total embodied emissions. These sectors directly or indirectly transferred a large part of carbon emissions through critical industrial supply chains. These results demonstrate that curbing emissions generated by carbon-intensive source sectors and reducing purchases of energy and material-intensive intermediate products could contribute to reducing the total embodied emissions of ICT sector. The most efficient way to abate embodied emissions of ICT sector would be to systematically optimize ICT supply chains, starting with upstream energy and materials production and proceeding to the final demand for ICT products or services. Therefore, carbon management policies should not be just directed to ICT sector itself but to upstream industrial chains.

The embodied carbon emissions of ICT sector maintained a steady growth trend over the study period. Although production-side factors (i.e. improvements in emission intensity and production structure) contributed to reducing the embodied emissions, the demand-side factors, i.e. ICT domestic consumption, investment, and export, offset the reduction effect. The export of ICT devices such as *computer*, *communication equipment* and *electronic components* largely contributes to emission growth. In contrast, energy and material efficiency improvements in upstream production sectors related to *electricity* and *metal smelting and pressing* are the major factors slowing the growth. These results remind us that adjusting the final demand level or structure of ICT sector may help achieve more cost-effective reductions in the absolute amounts of embodied emissions.

In summary, we recommend that embodied carbon impacts be considered while formulating industrial ICT development strategies such as setting carbon control target for China's action plan of "Internet plus", which might drive the emissions growth by boosting ICT investment in various traditional industries. As an intensive embodied carbon sector, the roles of ICT sector in emission reduction should be attached equivalent importance while establishing sector-level climate mitigation polices such as developing carbon accounting standards for key ICT subsectors and products. The mechanisms of the formation and change of ICT embodied emissions are complicated. As such, it is essential to implement an integrated management strategy that incorporates sector-specific, supply chain-wide, and economic driver-based carbon mitigation measures. Comprehensive identifying production and demand-side factors systematically reveals carbon abatement potentials, highlighting important implications for the low-carbon transition of ICT sector in the future.

Acknowledgements

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Appendix A. Proof of Eq. (4)

Assuming there are K sectors in the economic system, an input-output system can be classified into I sectors belonging to the ICT subsystem, and N sectors belonging to the non-ICT subsystem. The basic Leontief model can be expressed as:

$$\begin{pmatrix} A_{NN} & A_{NI} \\ A_{IN} & A_{II} \end{pmatrix}\begin{pmatrix} x^N \\ x^I \end{pmatrix} + \begin{pmatrix} y^N \\ y^I \end{pmatrix} = \begin{pmatrix} x^N \\ x^I \end{pmatrix} \tag{A.1}$$

where the subscripts and superscripts denote the group of accounts N and I, respectively. In expression (A.1), $A = \begin{pmatrix} A_{NN} & A_{NI} \\ A_{IN} & A_{II} \end{pmatrix}$ represents a direct requirement coefficient matrix; $x = \begin{pmatrix} x^N \\ x^I \end{pmatrix}$ is the column vector of sectoral output, in which x^I denotes the production of ICT subsectors and x^N denotes the production of non-ICT sectors; and $y = \begin{pmatrix} y^N \\ y^I \end{pmatrix}$ is the column vector of final demand, in which y^I denotes the final demand of ICT subsectors and y^N denotes the final demand of non-ICT sectors. When solving the sectoral output as $x = (I - A)^{-1}y = Ly$, the expression (A.1) can be rewritten as:

$$\begin{pmatrix} A_{NN} & A_{NI} \\ A_{IN} & A_{II} \end{pmatrix}\begin{pmatrix} L_{NN} & L_{NI} \\ L_{IN} & L_{II} \end{pmatrix}\begin{pmatrix} y^N \\ y^I \end{pmatrix} + \begin{pmatrix} y^N \\ y^I \end{pmatrix} = \begin{pmatrix} x^N \\ x^I \end{pmatrix} \tag{A.2}$$

Expression (A.2) can be rewritten as:

$$\begin{aligned} &(A_{NN}L_{NN} + A_{NI}L_{IN})y^N + (A_{NN}L_{NI} + A_{NI}L_{II})y^I + y^N = x^N \\ &(A_{IN}L_{NN} + A_{II}L_{IN})y^N + (A_{IN}L_{NI} + A_{II}L_{II})y^I + y^I = x^I \end{aligned} \tag{A.3}$$

The two equations in expression (A.3) give us the production of the ICT and non-ICT subsystems. Given our interest in analyzing the embodied carbon emissions in the ICT subsystem, we interpret the equations as follows.

The first equation, showing the total production of the non-ICT subsystem, can be divided into two parts. The term $(A_{NN}B_{NI} + A_{NI}B_{II})y^I$ shows the production of non-ICT sectors required to cover the final demand of ICT sector. Therefore, we define it as an *upstream supply component*. The remaining summands in the first equation show the production of non-ICT needed to cover the final demand of non-ICT itself.

In the second equation, the summand $(A_{IN}B_{NI} + A_{II}B_{II})y^I + y^I$ shows the production that ICT subsystem needed to cover the intermediate and final demand of the ICT subsectors themselves. It can be interpreted as a *self-supply component*.

To transform expression (A.3) into an emission model, we use vectors f^I and f^N, which contain the CO_2 emission coefficients (measured by CO_2 emissions per unit sectoral output) of the ICT subsectors and non-ICT sectors, respectively. By considering these vectors, the CO_2 emissions embodied in non-ICT and ICT production to cover the final demand of ICT equals:

$$ExC = f^N(A_{NN}L_{NI} + A_{NI}L_{II})y^I$$

$$InC = f^I(A_{IN}L_{NI} + A_{II}L_{II} + I)y^I \tag{A.4b}$$

The term $f^N(A_{NN}B_{NI} + A_{NI}B_{II})y^I$ in Eq. (A.4a) shows the CO_2 emissions embodied in the production of non-ICT sectors. Therefore, we can define it as an *external carbon component* (*ExC*). The term $f^I(A_{IN}B_{NI} + A_{II}B_{II} + I)$ y^I in Eq. (A.4b) shows the emissions embodied in the production of ICT subsystem and can be interpreted as an *internal carbon component* (*InC*).

These expressions show the emissions originated from the upstream sectors and ICT subsectors themselves. Thus, the total embodied emissions of the ICT subsystem (*EC*) can be expressed as:

$$EC = ExC + InC \tag{A.5}$$

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2019.04.014.

References

Alcántara, V., Padilla, E., 2009. Input-output subsystems and pollution: an application to the service sector and CO_2 emissions in Spain. Ecol. Econ. 68 (3), 905–914.

Andrae, A.S., Hu, L., Liu, L., Spear, J., Rubel, K., 2017. Delivering tangible carbon emission and cost reduction through the ICT supply chain. International Journal of Green Technology 3, 1–10.

Ang, B.W., 2005. The LMDI approach to decomposition analysis: a practical guide. Energy Policy 33 (7), 867–871.

Ang, B.W., Liu, F.L., Chew, E.P., 2003. Perfect decomposition techniques in energy and environmental analysis. Energy Policy 31 (14), 1561–1566.

Asongu, S.A., Le Roux, S., Biekpe, N., 2017. Environmental degradation, ICT and inclusive development in Sub-Saharan Africa. Energy Policy 111, 353–361.

Asongu, S.A., Le Roux, S., Biekpe, N., 2018. Enhancing ICT for environmental sustainability in sub-Saharan Africa. Technol. Forecast. Soc. Chang. 127, 209–216.

Atkinson, R.D., Mckay, A.S., 2007. Digital prosperity: understanding the economic benefits of the information technology revolution. Social Science Electronic Publishing 2, 64.

Belkhir, L., Elmeligi, A., 2018. Assessing ICT global emissions footprint: trends to 2040 & recommendations. J. Clean. Prod. 177, 448–463.

Berndt, E.R., Rappaport, N.J., 2001. Price and quality of desktop and mobile personal computers: a quarter-century historical overview. Am. Econ. Rev. 91 (2), 268–273.

Butnar, I., Llop, M., 2011. Structural decomposition analysis and input-output subsystems: changes in CO_2 emissions of Spanish service sectors (2000–2005). Ecol. Econ. 70 (11), 2012–2019.

Cecere, G., Corrocher, N., Gossart, C., Ozman, M., 2014. Technological pervasiveness and variety of innovators in green ICT: a patent-based analysis. Res. Policy 43 (10), 1827–1839.

Chen, S., Chen, B., 2017. Changing urban carbon metabolism over time: historical trajectory and future pathway. Environmental Science & Technology 51 (13), 7560–7571.

Chun, H., Kim, J.W., Lee, J., 2015. How does information technology improve aggregate productivity? A new channel of productivity dispersion and reallocation. Res. Policy 44 (5), 999–1016.

Collard, F., Fève, P., Portier, F., 2005. Electricity consumption and ICT in the French service sector. Energy Econ. 27 (3), 541–550.

Davis, S.J., Caldeira, K., 2010. Consumption-based accounting of CO_2 emissions. Proc. Natl. Acad. Sci. U. S. A. 107 (12), 5687–5692.

Dietzenbacher, E., Los, B., 1998. Structural decomposition techniques: sense and sensitivity. Econ. Syst. Res. 10 (4), 307–324.

Egilmez, G., Kucukvar, M., Tatari, O., 2013. Sustainability assessment of US manufacturing sectors: an economic input-output-based frontier approach. J. Clean. Prod. 53, 91–102.

Emmenegger, M.F., Frischknecht, R., Stutz, M., Guggisberg, M., Witschi, R., Otto, T., 2006. Life cycle assessment of the mobile communication system UMTS: towards eco-efficient systems. Int. J. Life Cycle Assess. 11 (4), 265–276.

Ercan, M., Malmodin, J., Bergmark, P., Kimfalk, E., Nilsson, E., 2016. Life cycle assessment of a smartphone. The 4th International Conference on ICT for Sustainability (ICT4S 2016).

Feng, K., Davis, S.J., Sun, L., Hubacek, K., 2015. Drivers of the US CO_2 emissions 1997–2013. Nat. Commun. 6, 7714.

Fettweis, G., Zimmermann, E., 2008, September. ICT Energy Consumption-trends and Challenges. The 11th international symposium on wireless personal multimedia communications, Sep. Lapland, Finland, p. 2008.

Feuerriegel, S., Bodenbenner, P., Neumann, D., 2016. Value and granularity of ICT and smart meter data in demand response systems. Energy Econ. 54, 1–10.

Gao, G., Chen, M., Wang, J., Yang, K., Xian, Y., Shi, X., Wang, K., 2019. Sufficient or insufficient: assessment of the intended nationally determined contributions (INDCs) of the world's major greenhouse gas emitters. Frontiers of Engineering Management 1–19.

Gemechu, E.D., Butnar, I., Llop, M., Castells, F., 2012. Environmental tax on products and services based on their carbon footprint: a case study of the pulp and paper sector. Energy Policy 50, 336–344.

Global e-Sustainability Initiative (GeSI), 2015. SMARTer2030, ICT Solutions for 21st Century Challenges. Belgium, GeSI, Accenture Strategy.

Guan, D., Hubacek, K., Weber, C.L., Peters, G.P., Reiner, D.M., 2008. The drivers of Chinese CO_2 emissions from 1980 to 2030. Glob. Environ. Chang. 18 (4), 626–634.

Higón, D.A., Gholami, R., Shirazi, F., 2017. ICT and environmental sustainability: a global perspective. Telematics & Informatics 34 (4), 85–95.

Honee, C., Hedin, D., St-Laurent, J., Froling, M., 2012. Environmental performance of data centres - a case study of the Swedish National Insurance Administration. Electronics Goes Green 11, 1–6.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, edited, IGES.

Jiang, X., Liu, Y., 2015. Global value chain, trade and carbon: case of information and communication technology manufacturing sector. Energy for Sustainable Development 25, 1–7.

Joyce, P.J., Finnveden, G., Håkansson, C., Wood, R., 2019. A multi-impact analysis of changing ICT consumption patterns for Sweden and the EU: indirect rebound effects and evidence of decoupling. J. Clean. Prod. 211, 1154–1161.

Lenzen, M., 2003. Environmentally important paths, linkages and key sectors in the Australian economy. Struct. Chang. Econ. Dyn. 14 (1), 1–34.

Liu, S., Tian, X., Cai, W., Chen, W., Wang, Y., 2018a. How the transitions in iron and steel and construction material industries impact China's CO_2 emissions: comprehensive analysis from an inter-sector linked perspective. Appl. Energy 211, 64–75.

Liu, Y., Shi, X., Laurenceson, J., 2018b. Are China's exports crowding out or being crowded out? Evidence from Japan's imports. China & World Economy 26 (4), 1–23.

Loo, B.P., Wang, B., 2017. Progress of e-development in China since 1998. Telecommun. Policy 41 (9), 731–742.

Malmodin, J., Lundén, Dag, 2016. The Energy and Carbon Footprint of the ICT and E&M Sector in Sweden 1990–2015 and beyond. ICT for Sustainability.

Malmodin, J., Moberg, Å., Lundén, D., Finnveden, G., Lövehagen, N., 2010. Greenhouse gas emissions and operational electricity use in the ICT and entertainment & media sectors. J. Ind. Ecol. 14 (5), 770–790.

Melville, N.P., 2010. Information systems innovation for environmental sustainability. MIS Q. 34 (1), 1–21.

Mi, Z., Meng, J., Guan, D., Shan, Y., Liu, Z., Wang, Y., Wei, Y.M., 2017. Pattern changes in determinants of Chinese emissions. Environ. Res. Lett. 12 (7), 074003.

Miller, R.E., Blair, P.D., 2009. Input-Output Analysis: Foundations and Extensions. Cambridge University Press.

Montserrat, L.C., Melisande, C., Giuditta, D.P., Sofia, S., Riccardo, R., 2018. 2018 PREDICT Dataset. European Commission (Joint Research Centre (JRC)).

Moyer, J.D., Hughes, B.B., 2012. ICTs: do they contribute to increased carbon emissions? Technol. Forecast. Soc. Chang. 79 (5), 919–931.

National Bureau of Statistics of China (NBSC), 2006. Input-Output Table of China (2002). China Statistics Press, Beijing.

National Bureau of Statistics of China (NBSC), 2009. Input-Output Table of China (2007). China Statistics Press, Beijing.

National Bureau of Statistics of China (NBSC), 2013. China Price Statistical Yearbook (2013). China Statistics Press, Beijing.

National Bureau of Statistics of China (NBSC), 2015. Input-Output Table of China (2012). China Statistics Press, Beijing.

National Bureau of Statistics of China (NBSC) (2017a). Industrial Classification for National Economic Activities (GB/T 4754-2017). Available at: http://www.stats.gov.cn/tjsj/tjbz/hyflbz/ (in Chinese).

National Bureau of Statistics of China (NBSC), 2017b. China Price Statistical Yearbook (2017). China Statistics Press, Beijing.

National Development and Reform Commission of China (NDRC), 2011. The 12th Five-Year Plan for Economic and Social Development of the people's Republic of China, National Development and Reform Commission, Beijing.

National Development and Reform Commission of China (NDRC), 2014. The People's Republic of China National Greenhouse Gas Inventory 2005. China Environmental Science Press, Beijing.

Olesen, K., Myers, M.D., 2013. Trying to improve communication and collaboration with information technology. Inf. Technol. People 12 (4), 317–332.

Olivier, J.G.J., Janssens-Maenhout, G., Muntean, M., Peters, J.A.H.W., 2016. Trends in global CO_2 emissions: 2016 report. European Commission, Joint Research Centre (JRC), Directorate C - Energy, Transport and Climate; PBL Netherlands Environmental Assessment Agency, The Hague. JRC103425, PBL2315 (November 2016).

Oshita, Y., 2012. Identifying critical supply chain paths that drive changes in CO_2 emissions. Energy Econ. 34 (4), 1041–1050.

Owen, A., Wood, R., Barrett, J., Evans, A., 2016. Explaining value chain differences in MRIO databases through structural path decomposition. Econ. Syst. Res. 28 (2), 243–272.

Pan, C., Peters, G.P., Andrew, R.M., Korsbakken, J.I., Li, S., Zhou, D., Zhou, P., 2017. Emissions embodied in global trade have plateaued due to structural changes in China. Earth's Future 5 (9), 934–946.

Peters, G.P., Weber, C.L., Guan, D., Hubacek, K., 2007. China's growing CO_2 emissions—a race between increasing consumption and efficiency gains. Environmental Science & Technology 41 (17), 5939–5944.

Pohl, J., Hilty, L.M., Finkbeiner, M., 2019. How LCA contributes to the environmental assessment of higher order effects of ICT application: a review of different approaches. J. Clean. Prod. 219, 698–712.

Røpke, I., 2012. The unsustainable directionality of innovation–the example of the broadband transition. Res. Policy 41 (9), 1631–1642.

Sanou, B., 2017. ICT facts and figures 2017. International Telecommunication Union https://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2017.pdf.

Shabani, Z.D., Shahnazi, R., 2019. Energy consumption, carbon dioxide emissions, information and communications technology, and gross domestic product in Iranian economic sectors: a panel causality analysis. Energy 169, 1064–1078.

Simon, J.P., 2014. The ICT Landscape in Brazil, India, and China (No. JRC92241) (Joint Research Centre (Seville site).

Skelton, A., Guan, D., Peters, G.P., Crawford brown, D., 2011. Mapping flows of embodied emissions in the global production system. Environmental Science & Technology 45 (24), 10516–10523.

State Council, 2017. Opinions about Further Expanding and Upgrading the Potential of Information Consumption. State Council of the People's Republic of China, Beijing.

Su, B., Ang, B.W., 2012. Structural decomposition analysis applied to energy and emissions: some methodological developments. Energy Econ. 34 (1), 177–188.

Su, B., Ang, B.W., 2013. Input-output analysis of CO_2 emissions embodied in trade: competitive versus non-competitive imports. Energy Policy 56 (5), 83–87.

Su, B., Huang, H.C., Ang, B.W., Zhou, P., 2010. Input-output analysis of CO_2 emissions embodied in trade: the effects of sector aggregation. Energy Econ. 32 (1), 166–175.

Sun, Y., Zou, X., Shi, X., Zhang, P., 2019. The economic impact of climate risks in China: evidence from 47-sector panel data, 2000–2014. Nat. Hazards 95 (1–2), 289–308.

Thakur, S., Chaurasia, A., 2016. Towards green cloud computing: Impact of carbon footprint on environment. Cloud System and Big Data Engineering (pp.209-213). IEEE.

United Nations, 1999. Handbook of input-output table compilation and analysis, studies in methods, Handbook of National Accounting. Series F, No. 74. New York.

Wang, Q., Chiu, Y.H., Chiu, C.R., 2015. Driving factors behind carbon dioxide emissions in China: a modified production-theoretical decomposition analysis. Energy Econ. 51, 252–260.

Wang, Q., Hang, Y., Su, B., Zhou, P., 2018. Contributions to sector-level carbon intensity change: an integrated decomposition analysis. Energy Econ. 70, 12–25.

Weber, C.L., Olivetti, E.A., Williams, E.D., 2010. Data and methodological needs to assess uncertainty in the carbon footprint of ICT products. IEEE International Symposium on Sustainable Systems and Technology. IEEE, p. 1.

Williams, E., 2011. Environmental effects of information and communications technologies. Nature 479 (7373), 354–358.

World Bank, 2012. World Development Indicators 2012. World Bank Publications.

Yang, J., Chen, B., 2014. Carbon footprint estimation of Chinese economic sectors based on a three-tier model. Renew. Sustain. Energy Rev. 29 (29), 499–507.

Yang, S., Shi, X., 2018. Intangible capital and sectoral energy intensity: evidence from 40 economies between 1995 and 2007. Energy Policy 122, 118–128.

Zhang, C., Liu, C., 2015. The impact of ICT industry on CO_2 emissions: a regional analysis in China. Renew. Sust. Energ. Rev. 44, 12–19.

Zhang, P., Shi, X., Sun, Y., Cui, J., Shao, S., 2019. Have China's provinces achieved their targets of energy intensity reduction? Reassessment based on nighttime lighting data. Energy Policy 128, 276–283.

Zhou, D., Zhou, X., Xu, Q., Wu, F., Wang, Q., Zha, D., 2018a. Regional embodied carbon emissions and their transfer characteristics in China. Struct. Chang. Econ. Dyn. 46, 180–193.

Zhou, X., Zhou, D., Wang, Q., 2018b. How does information and communication technology affect China's energy intensity? A three-tier structural decomposition analysis. Energy 151, 748–759.